Airborne Electromagnetic Time Domain System, Computer Product and Method

Field of the Invention

This invention relates in general to the field of airborne geological mapping. This invention further relates to an apparatus for conducting geological surveying using an electromagnetic time domain method.

Background of the Invention

Time Domain Electromagnetic (TDEM) surveying is a rapidly developing area of geophysical surveying. It encompasses ground based and airborne applications. TDEM geological mapping involves equations for calculating the value of electromagnetic fields that are time dependent. Geological data is then inferred from the electromagnetic field data based on resistivity factors, in a manner that is known.

The TDEM method was originally designed for exploration of conductive ore bodies buried in resistive bedrock, but at the present time it is also used extensively in general geological mapping, in hydrogeology, in environmental investigations etc.

The method involves generating periodic magnetic field pulses penetrating below the Earth surface. Turning off this magnetic field at the end of each pulse causes an appearance of eddy currents in geological space. These currents then gradually decay and change their disposition and direction depending on electrical resistivity and geometry of geological bodies. The electromagnetic fields of these eddy currents (also called transient or secondary fields) are then measured above the Earth surface and used for mapping and future geological interpretation in a manner that is known.

The common technical means to generate magnetic field pulses is a known transmitter generally consisting of a loop of wire or a multi-turn coil connected to the output of a known electrical current pulse generator or transmitter driver. The typical size of a transmitter coil is a few meters in diameter for an airborne device and up to hundreds of meters for ground systems. Generally, the bigger the transmitter coil diameter the stronger its magnetic moment, which then results in deeper and more accurate investigations.

An additional multi-turn coil or an x-y-z coil system usually serves as a receiver or sensor for the secondary electromagnetic field. Magnetometers are also applicable for this purpose. Received signals are digitised by a known analog to digital converter (ADC) and processed and stored by computer.

The advantage of airborne TDEM systems is the speed with which ground that can be covered in geological surveying. However, there are a number of technical problems in designing airborne TDEM systems based on prior art.

The transmitted electromagnetic fields generally generate eddy currents not only in the Earth but also in the proximate metallic parts including those of the system and the aircraft body. The secondary fields of these currents behave as a noise due to typical instability of the system geometry and thermal changes in conductors. This noise impacts the survey data by generally decreasing their reliability for extrapolating geological data therefrom.

The most common way to minimise this noise is by keeping the receiver at an adequate distance from the transmitter driver. The result of this spaced apart relationship between the transmitter driver and the receiver is

that the secondary fields of the eddy currents in the Earth are comparable with secondary fields of local metal parts and therefore noise level is negligible. This type of solution is used in the TDEM systems branded "GEOTEM" and "MEGATEM" of (FUGRO AIRBONE SURVEYS LTD) GEOTERREX PTY. LTD. This particular solution includes a bird towed behind a fixed-wing aircraft on a tow cable approximately 130 meters long.

Another prior art TDEM system consists of a helicopter towed system manufactured by T.H.E.M Geophysics Inc. This system uses a helium balloon to keep its sensor suspended at a distance apart from the transmitter system.

One of the disadvantages of these prior art solutions is that there is relatively poor horizontal resolution of the system due to the relatively long distance between transmitter coil and receiver sensor. Another disadvantage is difficulties of system mechanical management in start/landing and in flight manoeuvres.

Another prior art method currently used to minimise this kind of noise is to cancel the transmitter primary field localised in metal parts of the system using special coils producing in this local area a magnetic field having opposite direction to the main field of the transmitter coils. This technology is used in the AEROTEM™ branded solution of Aeroquest Ltd. in order to minimise the secondary fields in the metal parts of the transmitter electronics, which instead they locate in the towed bird. This solution requires a high level of system mechanical rigidity. In turn, it leads to heavier frame construction. The heavier frame results in a number of disadvantages. In particular the heavier frame makes transportation of the bird difficult. The production costs and fuel costs associated with manufacturing and use of the AEROTEM™ solution are also relatively high.

More importantly, because of the need for a rigid frame having a relatively significant weight, a frame with a generally smaller transmitter coil diameter is selected resulting in a lower transmitter dipole moment. This generally results in insufficient transmitter dipole moment to make deeper measurements.

Another problem with the prior art solutions is that they do not easily permit exploiting optimal system geometry, that is the receiver in the centre of the transmitter coil. A relatively large voltage is induced in the receiver coil by each of the magnetic field pulses. But this relatively high voltage in turn renders the receiver preamp saturated and therefore inoperative during system measurement time for a short period after this pulse. This is an important and necessary time for making measurements of the Earth's response.

As a result, the solution of existing systems is to place the system receiver at a distance away from the transmitter where the transmitted pulse is much lower since the strength of this field diminishes as the inverse cube of the distance. However, this then results in a departure from the optimal system geometry.

In the case of the AEROTEM ™ system, the method of dealing with this large voltage pulse while maintaining optimal system geometry, i.e. receiver in centre of transmitter coil, is to place the receiver coil inside a bucking coil carrying the anti-phased transmitter current so as to cancel a large part of the voltage pulse induced in the receiver coil during the transmitter "ON TIME" while not substantially affecting the reception of the secondary field from the Earth.

This approach works well to solve the problem of this on-time voltage pulse problem, however, the process of accurately bucking this signal again mandates the rigid geometry of all parts including the receiver coil. This rigid

mounting precludes the proper vibration isolation of the receiver coil thus unwanted mechanical vibration influences the receiver coil so as to induce electrical interference thereby reducing sensitivity.

Another technical problem is how to produce maximum magnetic moment in the transmitter coil using minimum weight, size and electrical power. In the above-mentioned systems a significant part of the total weight is used for the structure and power sources.

Another problem is the air drag of the bird during flight. Complicated support structures with large effective surface areas create excessive drag. This limits possible flight speed increasing survey cost.

Another limitation of the previously mentioned systems is the limitation on the maximum transmitter diameter and therefore obtainable dipole moment. A maximum diameter for these systems is generally attained relatively quickly because the rigidity criterion mandates significant weight of the structure. This stiffness factor forces this type of design to reach the maximum allowable weight for helicopter use before a desirable diameter is attained.

Summary of the Invention

An object of the present invention is to provide a TDEM system that provides improved sensor resolution.

Brief Description of the Drawings

Figure 1 illustrates the apparatus of the present invention in an airborne position, in this case towed from a helicopter.

Figure 2 illustrates the tow assembly of the present invention in a perspective view.

Figure 3 illustrates the tow assembly of the present invention in an elevation view.

Figure 4 illustrates the tow assembly of the present invention in a top view thereof, and further showing a bottom view of the receiver section of the tow assembly.

Figure 5 illustrates the structure of the transmitter section of the tow assembly in a partial cut-away view of a joint section thereof.

Figure 5a illustrates the structure of the transmitter section of the tow assembly in a partial view thereof at a joint section.

Figure 5b illustrates the structure of the receiver section in a cut-view thereof.

Figure 5c is a further cut-away view of the receiver section.

Figure 6 is a view of the stabilizer section of the tow assembly, in accordance with one embodiment thereof.

Figure 7 is a chart illustrating the survey data generated by the tow assembly of the present invention in operation.

Figure 8 is a system resource chart illustrating the resources of the system of the present invention.

Figure 9 is a program resource chart that illustrates the resources of the computer product of the present invention.

In the drawings, one embodiment of the invention is illustrated by way of example. It is to be expressly understood that the description and drawings are only for the purpose of illustration and as an aid to understanding, and are not intended as a definition of the limits of the invention.

Detailed Description of the Preferred Embodiment

The present invention consists of an airborne TDEM survey system **10**. The TDEM survey system **10** includes an aircraft **12** and a tow assembly **14**. Fig. 1 illustrates an aircraft **12** that is a helicopter, however, other aircraft such as airplanes having desirable take-off and landing attributes from a geological survey perspective could also be used.

It should be understood that in one aspect of the present invention the tow assembly **14** is separate from the aircraft **12** but then attached thereto by a suitable attachment means. Provided that the flexible frame discussed below is provided, the tow assembly **14** could be integrated with an aircraft **12** to produce a geological surveying aircraft including a tow assembly **14** in accordance with the present invention.

The tow assembly **14** of the present invention generally includes a flexible frame **15**, as illustrated in Fig 2. The flexible frame includes a transmitter section **16** and a receiver section **18**. In accordance with the present invention, the receiver section **18** is in most implementations substantially disposed in the center of the transmitter section **16**. This generally provides the optimal geometry referred to above.

One aspect of the present invention is the ease in which the tow assembly **14** can be assembled, disassembled and therefore transported from one location to another. Another aspect of the present invention is that the

flexible frame **15** overall can be adjusted in terms of its size to suit for particular applications.

To this end, the transmitter section **16**, in a particular implementation of the present invention, as shown in Fig. 4, consists of a substantially octagonal support frame **20**. The support frame **20** consists of a plurality of substantially tube sections **22**. As best shown in Figure 5a, the various tube sections at the corners are interconnected by means of elbow sections **24**.

The tube sections **22** can consist of a single piece, or multiple pieces that can be interconnected. The tubing used in the present invention consists of composite material tubing such as fiberglass or Kevlar. Alternatively, the components (described below) of the support frame **20** can be made of carbon fiber for increased strength, preferably with non-conductive areas along the length of one or more of the components to avoid the anomaly that would be caused by a complete conductive loop.

One embodiment of the support frame **20** of the present invention described consists of tube sections **22** and elbow sections **27** whereby adding additional tube sections **22** or multiple pieces together providing one of the tube sections **22**, as well as additional elbow sections **24**, provides a support frame **20** having a greater surface area. It should be understood that tube sections **22** and elbow sections **24** can be added or removed to increase or decrease the surface area.

While the support frame **20** shown in the Figures has an octagonal shape, it should be understood that the present invention also contemplates support frames **15** having other polygonal shapes, although a polygonal shape approximating a circular shape is generally preferred. It should be understood that the modular pieces together providing the support frame **20** can be modified to provide a support frame **20** having a substantially circular profile. Also, in applications of the present invention where transportation and

adjustment of the size of the flexible frame **15** is not required, the support frame can be provided in a single unitary construction, as opposed to the modular construction described above.

It should be understood that the construction of the support frame **20** described herein enables a relatively large surface area while the support frame **20** of the present invention is also relatively lightweight. By way of example only, it was found that the construction described herein easily permitted an increase of the transmitter loop diameter (or more than) up to 26 meters while permitting maneuvering of the aircraft **10** with the tow assembly **14** in tow.

The support frame **20**, as best shown in Fig. 3, is suspended using rope **26** from its corners (in the polygonal construction thereof). In a circular construction of the support frame **20**, the support frame **20** would be suspended by rope at substantially equidistant points along the circumference thereof.

The rope **26** is then attached to a central tow cable in a manner that is known.

The support frame **20** bears a known multi-turn transmitter coil **28** so as to provide the transmitter function of the transmitter section **16**. In the embodiment of the invention shown in Fig. 3, the transmitter coil **28** is strung along the bottom of the support frame **20** by attaching the transmitter coil from multiple points along the support frame **20** by a suitable form of attachment. Alternatively, the transmitter coil **28** can be disposed inside the support frame **20**.

In another aspect of the support frame construction of the present invention, the invention also provides flexibility in the ability to make changes

in receiver loop turns and loop area, and also by adding receiver coils in other axes, without change to the to disclosed tow assembly **14** configuration.

In accordance with the present invention, a known electronic transmitter driver **32** that feeds the transmitter coil **28** is installed in the aircraft **12**. The transmitter driver **32** is connected to the transmitter coil **28** as illustrated in Figure 8. This connection is generally provided by wiring the transmitter coil **28** to the transmitter driver **32** along the central tow cable and at least one of the ropes **26** supporting the support frame **20**.

The flexible frame **20** also includes a stabilizer as shown in Fig. 1. The stabilizer **36**, as best shown in Fig. 6, generally has a stabilizer frame **37** that supports an aerodynamically shaped stabilizer tube **38**. The stabilizer **34** is generally made of plastic and is connected to the support frame **20** at a point by means of a suitable attachment.

In an embodiment of the present invention, as best shown in Fig. 4, a series of tension ropes **40** are attached to the support frame **20** at various points and then connected to a central hub **42**. In the particular embodiment of the support frame **20** shown in Fig. 4, having an octagonal shape, the tension ropes **40** are attached to the corners of the support frame **20**. The tension ropes **40** provide some rigidity to the support frame **20**.

As best shown in Fig. 4, the receiver section **18** also consists of a plurality of interconnected receiver tube sections **44** together providing a receiver frame **45**. These receiver tube sections **44** are also made of plastic and are similar in construction to the tube sections **22** and elbow sections **24** that provide the structure of the support frame **20** in the particular embodiment thereof described herein. The tube sections **44** generally provide, however, a receiver section **18** having a much smaller surface area than that of the receiver section **18** or support frame **20**. As best shown in Figure 5a, the

various receiver tube sections **44** are interconnected by means of receiver elbow sections **46**.

Much as in the case of the support frame **20**, the receiver frame **45** has a modular construction whereby additional receiver tube sections **44** and receiver elbow sections **46** may be added to provide a receiver frame **45** having a greater or lesser surface area. Also similarly, the receiver frame **45** can in accordance with the present invention be provided in accordance with alternate polygonal structures or in fact a circular structure. In addition, a unitary construction as opposed to a modular construction may be desirable.

In accordance with one embodiment of the present invention, the receiver frame **45** is mounted on the tension ropes **40** by leading the tension ropes **40** through a series of loops **48** disposed on the receiver frame **45** as best shown in Fig. 4.

The receiver frame **45** is provided with a sensor coil **50**. In accordance with an embodiment of the present invention, the sensor coil **50** is disposed inside a shell **52** disposed inside the receiver frame **45**, as shown in Figs. 5b and 5c. The shell **52** consists of plastic tubing similar to the tubing the receiver tube sections **44** and receiver elbow sections **46**, but having a smaller circumference.

In addition, the shell **52** is elastically suspended using a series of elastics **54** (one shown only) attached to points **54** along the inner wall of the receiver frame **45** tubing and elastically supporting the shell **52**. The sensor coil **50**, in turn, is elastically supported by a series of elastics **54** (one shown only) attached to points **56** along the inner wall of the shell **52**.

The elastic suspension of the sensor coil **50** inside the shell **52** minimizes the effect of vibration.

In one particular embodiment of the present invention, the sensor coil **50** output is connected to a non linear preamplifier **63** mounted in a box on the shell **52** outer surface (not shown). This is illustrated in Figure 8.

The result of the above is that metallic parts except wires and the preamplifier **63** are generally concentrated in the aircraft **12** far enough from field generating and the sensitive components of the flexible frame **12**. This results in relatively small parasitic eddy currents whereby useful signals dominate.

A further result of the tow assembly construction described above, is that the two assembly consists generally of the tubular fiberglass parts described above whereby generally more than a half of the bird weight belongs to transmitter coil wires.

Generally a transmitter coil **30** having relatively thick wires with low resistance that can reach higher intensity of the transmitting magnetic field is used. Of course, the overall weight must not exceed values that would otherwise unduly burden the aircraft **12** or negatively affect maneuverability.

In addition to the fiberglass or carbon fiber tubing, the tow assembly **14** uses the ropes discussed above. This reduces the need for additional plastic or metal spokes. The ropes reduce air drag and allows for higher flight speed.

As best illustrated in Figure 8, the system of the present invention also includes a signal-processing computer **58**. The computer **58** includes a known analog to digital converter device (ADC) **60**. The output of the preamplifier is connected in sequence to a known amplifier **62**, low pass filter **64** and then the ADC **60**, in a manner that is known. The ADC converts the analog data produced by the sensor coil **50** and preamplifier in combination to produce digital data for digital data conversion as described below.

The signal from the sensor coil **50**, which is proportional to dB/dt, goes through the amplifier **62** and low pass filter **62**. The ADC **60** continuously converts the signal to digits. The computer **58** includes a microprocessor (not shown) and is linked to a memory. A computer program **66** is installed on the computer **58** for analyzing the digital data to produce the survey data illustrated in Fig. 7. The computer program can produce arbitrary output waveforms including square, trapezoidal and triangular waveforms in order to meet the particular survey requirements. The computer program **66** also permits pulse repetition rate to be dynamically altered to lower repetition rates being more suitable for very conductive targets or higher for less conductive targets. Figure 9 illustrates the resources of this computer program.

The sensor coil **50** parameters define the necessary sensitivity so that the signal does not exceed the input range of the non linear preamplifier.

The preamplifier **63** is a differential amplifier with a specially designed, fast recovery, non-linear gain. In relation to the TDEM process, the differential amplifier has a high linear gain of the signal within a set range equal to the expected measurement signal level with the pulse off and turns the amplified signal to unity gain when the signal exceeds this limit during the "on" pulse. In that way the preamplifier limits output voltage during “ON TIME” pulse and provides low distortion and has fast recovery and high gain during off time.

This in turn allows the sensor coil **50** to be placed in the optimal position in the center of the transmitting section **16** without the need for any bucking of the primary transmitted pulse. This then allows the use merely of vibration isolation of the sensor coil **50** (as described above) thus increasing our signal to noise ratio.

By using this non-linear preamplifier method over the bucking method, a transmitter loop diameter and corresponding size of the support frame, as

well as the number of loop turns can be selected to suit particular geological targets simply and on site.

Alteration of these parameters in the context of a bucking system is generally discouraged because the bucking system would be lose effectiveness in the advent of such alteration. Thus the bucking method is generally less flexible than the present invention.

In another aspect of the invention, the support frame **20** is also adapted to measure the signal during the ~~off~~ on-time so as to provide in- phase information. This has been found to improve survey data, for example, in the case of ore bodies of relatively high conductance, for example, nickel. This is achieved by taking signal off of the transmitter coil **28**, or alternatively a separate receiver coil is looped tightly to the transmitter coil for this purpose.

In another aspect of the invention a current measuring unit (not shown) is added to the system of the present invention. The current measuring unit measures the residual currents circulating in the transmitter coil **28** during the "OFF" interval thereby enabling the system to minimize distortions caused by these residual currents to the earth response to the electromagnetic field pulse. This is especially important in the time immediately after the transmit pulse when current leakage and current oscillations may exist for a short time. These currents cause errors in the received signals. One implementation of the current measuring unit consists of an air-core transformer and preamplifier which is then connected to an AD converter. The transformer is preferably designed like a Rogowski coil which includes wide dynamic and frequency ranges, high stability and linearity of its characteristics and easy calibration. The primary winding of the transformer is connected in serial with the transmitter coil so that the current flowing through the coil generates emf=M * dI/dt at the secondary winding of the transformer. The signal-processing computer **58** is connected to the transformer and therefore sample signal therefrom much as the receiver signal and uses this data for further correction

of the receiver signal. In one particular implementation thereof the current measuring unit is housed in a box (not shown) and is mounted on the tow cable.

Other modifications are possible. For example, additional receiver coils oriented in the X -axis and/or the Y- axis can be added. The use of a mechanically flexible relationship between the transmitter coil and the receiver coil. This simplifies and greatly reduces the necessary weight of the support structure as well as allowing the user to use a much larger loop diameter thus giving the system higher dipole moment. The ability to rotate the entire structure 90 degrees so that the transmitter flies in the X-axis direction thus allowing for better detection of vertical conductive bodies.